MATERIALS CHARACTERIZATION 61 (2010) 913–922

available at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/matchar

# Plastic deformation and creep damage evaluations of type 316 austenitic stainless steels by EBSD

Rika Yoda[a,b,d,*], Toshinori Yokomaku[c], Nobuhiro Tsuji[d]

[a]Electronics Division, Kobelco Research Institute Inc., 1-5-5 Takatsuka-dai, Nishi-ku, Kobe, Hyogo 651-2271, Japan
[b]Department of Adaptive Machine Systems, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
[c]Engineering Mechanics Division, Kobelco Research Institute Inc., 1-5-5 Takatsuka-dai, Nishi-ku, Kobe, Hyogo 651-2271, Japan
[d]Department of Materials Science and Engineering, Graduate School of Engineering, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, 606-8501, Japan

ARTICLE DATA

*Article history:*
Received 10 May 2009
Received in revised form 6 May 2010
Accepted 10 May 2010

*Keywords:*
Electron backscatter diffraction (EBSD)
Average misorientation
Plastic deformation
Creep damage
Inelastic strain
Austenitic stainless steel

ABSTRACT

The inspection method of plastic and/or creep deformations has been required as the quantitative damage estimation procedure for structural components especially used in electric power plants. In this study, the method using electron backscatter diffraction (EBSD) was applied to the deformation and damage evaluation of austenitic stainless steels strained by tension or compression at room temperature and also tested in creep at high temperature. It was found that the value of Grain Average Misorientation (GAM) which showed the average misorientation for the whole observed area including over several dozen grains, was a very useful parameter for quantifying the microstructural change as either the plastic or creep strain increased. The unique linear correlation was obtained between GAM and plastic strain in tension and compression. For creep damage evaluation, the difference of grain average misorientation from the value of the unstrained specimen (ΔGAM) showed an excellent correlation with the inelastic strain below strain at which the tertiary creep began.



## 1. Introduction

In structural components for electric power or petro-chemical plants, residual stresses, caused by plastic deformation in metal forming and welding processes, may raise the stress corrosion cracking sensitivity or deteriorate the fatigue properties. Also, thermal and mechanical stresses at service temperatures may cause the life reduction by creep deformation. Therefore, the inspection method of plastic and/or creep deformation has been required as the quantitative damage estimation procedure for above structural components.

Various methods have been developed for this purpose [1], such as hardness measurement, *A-parameter* method using replicas of surface microstructure, ultrasonic, electric, magnetic, and X-ray methods. Hardness measurement is a very simple method, but it cannot distinguish hardening by plastic deformation from that by precipitation occurred at elevated temperatures. Surface replication method, such as *A-parameter* method to evaluate the void fraction, can be applied only to the materials including creep voids. Either ultrasonic, electric, magnetic or X-ray method, utilizes indirect parameters, such as ultrasonic amplitude, electric resistance, Barkhausen noise, and half breadth value of X-ray diffraction peak, each of which does not necessarily have a clear physical meaning of the deformation or damage itself.

* *Corresponding author*. Electronics Division, Kobelco Research Institute Inc., 1-5-5 Takatsuka-dai, Nishi-ku, Kobe, Hyogo 651-2271, Japan. Tel.: +81 78 992 6043; fax: +81 78 990 3062.
E-mail addresses: yoda.rika@kki.kobelco.com (R. Yoda), yokomaku.toshinori@kki.kobelco.com (T. Yokomaku), nobuhiro.tsuji@ky5.ecs.kyoto-u.ac.jp (N. Tsuji).

1044-5803/$ – see front matter 
doi:10.1016/j.matchar.2010.05.006

On the other hand, a method using electron backscatter diffraction (EBSD) detected in a scanning electron microscope (SEM) has the advantage that the degree of deformation or damage can be expressed quantitatively as a local change in crystal orientation of grains[2–13]. Also, the deterioration in quality of EBSD patterns is considered to correspond to a change in dislocation density caused by plastic strain [14–18]. The recent improvement of the equipment and analysis software is propelling the studies regarding damage evaluation by the EBSD method. It has been reported that local misorientation in grain increased with increasing plastic strain [5,19–28]. On the other hand, for creep damage evaluation of heat-resistant material, Takaku et al. [29] showed that the same tendency was obtained even during increasing creep strain in a Ni base superalloy. However, Fujiyama et al. [30] and Ohtani et al. [31] clarified that local misorientation decreased with creep strain in the material having martensitic structure, such as 10%Cr steel and type 403 stainless steel, respectively. Furthermore, Mitsuhara et al. [32] reported that three different parameters were suitable for three different creep regions in a 9–10%Cr steel. These results suggest that appropriate EBSD parameters for creep damage evaluation depend on the kind of materials or phases.

In this study, first, we evaluate the relationship between the Grain Average Misorientation (GAM), that is one of the parameters obtained by EBSD analysis, and the plastic strain in the most fundamental tensile and compressive deformation, using an austenitic stainless steel. Secondly, we discuss the applicability of this parameter as a measure of the creep damage and deformation.

## 2. Experimental Procedures

### 2.1. Materials

Two types of austenitic stainless steels are used in this study. One is a type 316 stainless steel (JIS-SUS316) that is a common material for high-temperature applications. The other is a type 316 nuclear grade stainless steel (ASTM type 316NG) for nuclear power plant component. The steels were solution-treated after hot rolling, and provided for the present experiments. The chemical compositions and tensile properties of the steels are summarized in Tables 1 and 2, respectively. The optical microstructures of the starting specimens solution-treated are shown in Fig. 1. Both steels show fully recrystallized microstructures, and the average grain diameters are 106 μm and 23 μm for type 316NG and type 316, respectively.

### 2.2. Tensile and Compression Deformation

The first purpose of this study is to clarify the relationship between some parameters obtained by EBSD analysis and plastic strain, in order to apply the EBSD method to various damage evaluations in real structural materials. Uniaxial deformation is the most fundamental deformation mode. Therefore, both tensile and compression deformations were adopted as uniaxial plastic deformation in this study.

**Table 2 – Tensile properties of the starting materials.**

| Material | Yield stress (MPa) | Tensile strength (MPa) | Elongation (%) | Reduction in area (%) |
|---|---|---|---|---|
| Type 316 | 287 | 607 | 60 | 74 |
| Type 316NG | 282 | 577 | 53 | 80 |

Round-bar tensile specimens 7 mm in diameter and 15 mm in gauge length, and cylindrical compression specimens 10 mm in diameter and 20 mm in length were machined from the type 316NG stainless steel plate. These specimens were deformed uniaxially in tension or compression, respectively, at room temperature. Both tensile and compression deformations were carried out at an initial strain rate of $3.3\times10^{-3}\,s^{-1}$ using SHIMADZU Autograph. The specimens were deformed up to four different strain levels: 0.87% engineering strain (true strain: $\varepsilon_{pl}$=0.0087), 2.82% ($\varepsilon_{pl}$=0.0278), 4.79% ($\varepsilon_{pl}$=0.0468) and 9.70% ($\varepsilon_{pl}$=0.0926) for tensile deformation, and 0.88% ($\varepsilon_{pl}$=0.0088), 2.84% ($\varepsilon_{pl}$=0.0288), 4.86% ($\varepsilon_{pl}$=0.0498) and 9.72% ($\varepsilon_{pl}$=0.102) for compression, respectively.

### 2.3. Creep Deformation

The round-bar creep specimens of 10 mm in diameter and 50 mm in gauge length, were machined from the type 316 stainless steel plate. Creep rupture tests were conducted at 600 °C under the applied stresses of 250, 270, 280 and 300 MPa and the corresponding rupture times ($t_r$) were 2600, 599, 409 and 156 h, respectively, as is shown in Fig. 2(a). Creep interruption tests were carried out under an applied stress of 270 MPa (rupture time = 599 h). Interruption times of the tests are 72, 144, 210, 300 and 419 h which correspond to the creep damage ratio (Dc = $t/t_r$, t; interruption time) of 0.12, 0.24, 0.35, 0.50 and 0.70, respectively. Creep curves of the interrupted specimens are shown in Fig. 2(b). The 316 steel showed typical creep behaviors.

### 2.4. EBSD Analysis

OIM (Orientation Imaging Microscopy™) system of EDAX/TSL attached to a field-emission SEM (FEI XL30S-FEG) was used for the EBSD analysis. The cross-section parallel to the stress axis in each specimen was polished using progressively finer grades of diamond paste, ranging from 6 μm to 1 μm and finally 0.25 μm in particle size, and then they were lightly

**Table 1 – Chemical compositions of the stainless steels studied.**

| Material | (mass%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cu | Ni | Cr | Mo | N |
| Type 316 | 0.05 | 0.26 | 1.28 | 0.033 | 0.029 | – | 10.0 | 16.99 | 2.01 | |
| Type 316NG | 0.016 | 0.43 | 1.54 | 0.02 | 0.0006 | 0.26 | 11.94 | 17.13 | 2.15 | 0.1 |